ARCTIC METEOROLOGY RESEARCH GROUP
DEPARTMENT OF METEOROLOGY
McGILL UNIVERSITY, MONTREAL

Climate Change over the Polar Ocean

I: The Radiation Budget

by

E. VOWINCKEL and SVENN ORVIG

PUBLICATION IN METEOROLOGY No. 79 | **January 1966**

U.S. ARMY MATERIEL COMMAND
U.S. ARMY NATICK LABORATORIES
NATICK, MASSACHUSETTS

Contract No. DA 19-129-AMC-490 (N)

Technical Report 66-8-ES

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TABLE OF CONTENTS

ABSTRACT

Climatic change results from changes in the terms of the energy equation. The present study consists of an analysis of possible changes in the radiation terms of the Polar Ocean energy budget.

The absorbed solar radiation at the surface depends mainly on clouds and surface albedo. These factors are discussed, and the absorbed solar radiation is presented for various extreme surface and atmospheric conditions.

The solar radiation absorbed in the atmosphere is next discussed. It is apparent that variations in the atmospheric short wave absorption are of rather small importance for climatic change.

There is greater possibility of variations in long wave radiation than of solar radiation. Theoretical polar atmospheres are discussed, with the consequent changes in the radiation balance. The conclusion appears that the atmosphere is at present adjusted in the best possible way for the conservation of energy.

Long wave heat fluxes have been calculated for the condition of an open Polar Ocean in winter and for a Polar Ocean completely frozen throughout the year.

It is concluded that, for <u>cloudless conditions,</u> there is little possibility for a change in the long wave balance in summer; the long wave balance would become much more negative in winter; the development of a

winter balance less negative than the present seems unlikely. Changes in surface conditions are much more important than changes in the atmosphere, for the total long wave radiation budget.

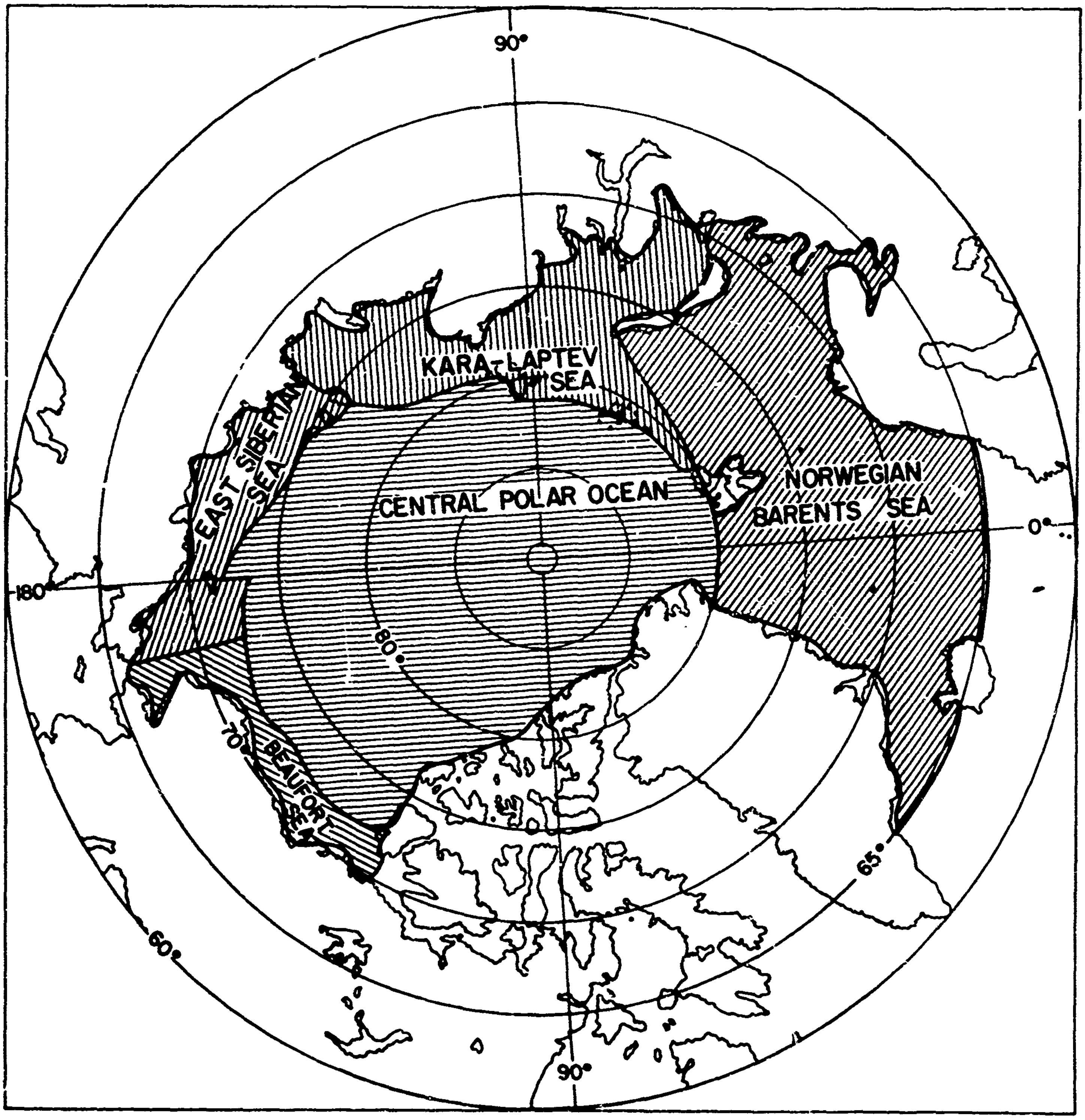
Various radiation budgets are presented, for different assumed conditions. The warmest surface conditions would occur with winter overcast and summer cloudless sky. The annual radiation balances would become:

with present Polar Ocean surface:	+ 23.9
with frozen surface:	+ 3.3 K cal cm^{-2}
with open ocean:	+ 47.1

The radiation budget is presented for an open Polar Ocean with cloud conditions such as presently found over the Norwegian Sea. It is apparent that the Polar Ocean is at present in a delicate radiational balance, and relatively minor variations in any term can result in a process leading to complete freeze-over or to complete melting.

The atmospheric heat advection required with an open Polar Ocean would decrease significantly. In winter, it is even possible that this term in the energy budget might become negative (heat export by winds from the Polar Ocean).

REGIONS
Fig. 1



All shaded areas make up the Arctic Ocean.
The Polar Ocean comprises the Arctic Ocean less the Norwegian-Barents Sea, i.e., it consists of the Central Polar Ocean plus the marginal seas.

INTRODUCTION

Climatic change results from a change in one or several of the terms of the energy balance equation. It can thus be studied either by determining the changes which have taken place in the various records (geological, botanical, climatological, etc.), or by analysing the present-day energy budget. From such an analysis one can ascertain the climatic changes which would occur as a result of different values for the various paramaters in the energy budget. The latter method will be used in the present investigation.

There are three different types of influences affecting the energy budget:

1. Geographical. A region may change its relative location (i.e., continental drift). The distribution of land-sea may change. Mountains may be built, or eroded.
2. Atmospheric. The circulation may change, resulting in changed conditions in certain regions. The composition of the atmosphere may change (e.g., CO_2 content, cloud amount).
3. Astronomical. The energy output from the sun may change. Solar energy might increase by collision with clouds of interstellar dust. Finally, orbital changes may give rise to changes in the energy budget.

In the present investigation it will be assumed that the

present-day geographical and astronomical conditions are fixed, and only variations in the atmospheric parameters will be assumed. Further, the chemical composition of the atmosphere will be regarded as constant.

This approach will allow quantitative statements to be made. The main difficulty is the close inter-dependency of the terms in the heat balance equation. At present it is difficult to make reasonable predictions of the complicated interactions subsequent to a change in even one of the terms in the energy budget.

In this part of the investigation there will be made no major attempt at predicting these interactions. It is proposed to determine first the possible variations in the radiation terms over the Polar Ocean. Later, the turbulent and advective terms will be treated,and the interactions will be considered at the end.

In previous publications the authors (1965) have discussed the various terms of the present-day heat budget over the Arctic Ocean, (Fig. 1).

The method used was to examine each term in the energy balance equation in turn, and to calculate for grid points monthly mean values of the various processes.

It became necessary to examine the existing literature on the water balance and heat flux into the Arctic Ocean. As contributions to this subject are found in a great number of different publications, and

as a large proportion is in Russian and not easily accessible, it was necessary to summarize the available information as completely as possible. The investigation was not undertaken for oceanographic purposes but for heat balance calculations. Therefore, all the more detailed oceanographic material was disregarded. However, much of this material will be found in the literature. Water flux and temperatures for the various ocean currents into and out of the Arctic were examined. Runoff and precipitation were also studied. Ice export by the various currents was treated, and the heat gain by formation and export of sea ice was calculated. Finally, water balance and heat flux estimates were obtained for the Arctic and Polar Oceans, with the annual total heat gain, including that of ice.

It next became necessary to calculate the amounts of solar radiation reflected from the various surfaces in the Arctic at different times of the year. Albedo is the ratio of the amount of radiation reflected by a surface to the amount incident upon it, expressed as a percentage. An Atlas was produced, containing a set of maps which can be used in climatological studies of the Arctic. The maps are monthly maps of mean albedo in wide class groups (20 per cent intervals). A companion report contains a monthly tabulation of those areas within 5° latitude belts, which have certain albedo values (5 per cent intervals). This tabulation, together with values of solar altitude and duration of daylight, was used to calculate energy

losses by reflection. The monthly maps which make up the Atlas were mainly compiled from published maps of the various parameters involved. They may be broken down into three groups: those concerned with sea areas, those concerned with land areas and those of a climatological nature. It should be noted that albedo information was included for winter months in areas with continuous darkness. This was done both for continuity and to stress the fact that the maps express surface conditions in terms of albedo. The companion volume contains tabulations of daylight duration for various latitudes at different times of the year. These tabulations were based, in the first instance, upon the monthly maps which made up the Atlas. In the Atlas the spatial distribution was shown visually, which necessitated the use of wide albedo groups (20% intervals). Such a wide grouping does not permit calculations to be made of net solar radiation in the Arctic. Therefore, in order to supply more detailed information, specific albedo values, based upon data given in the literature examined, were assigned to the classes used in the maps. Transitional zones, where applicable, were inserted by assuming a gradient of albedo between classes. Albedos were tabulated for both direct and diffuse radiation conditions where they differ significantly. The direct radiation albedo information was presented graphically for each month in the form of stereograms.

Cloud amount and duration of sunshine are generally used to estimate

direct and diffuse solar radiation income at the ground, where radiation instruments are not available. This method has serious drawbacks, and a consideration of cloud type is also necessary. The different elements required for the calculation of radiation income at the ground were studied for the arctic regions. Such calculation can give only general results, and measured values of radiation in the Arctic, with different cloud types, were therefore examined. The magnitude was discussed of the values in the Arctic of albedo of cloud tops, water content of clouds, ground albedo, and the effect of composite cloud types. From the results it was possible to construct tables which show the depletion for different combinations of cloud types.

Next, an attempt was made to evaluate cloud conditions north of 65°N. As more observations are now available than when previous cloud maps were constructed, it seemed that a new attempt at cloud mapping, on a monthly basis, would be justified. It proved impossible to use a uniform period of observation for the whole area, especially for the Asian Sector. The data used were most recent for the American Sector, oldest for Eurasia. The material was insufficient to permit monthly evaluations of cloud types, so the results were given for seasons. For cloud amount, monthly maps were constructed and grid point values tabulated. Seasonal maps of cloud types were constructed, and grid point tables prepared.

Latitudinal means of cloudiness show that there is high variability between seasons in the north, and rather stable conditions in the south. Only during a short transition period in May and again in October is there little difference in the average cloud amount over the whole arctic sector. The main regional types of cloudiness in the Arctic were discussed. These are: Norwegian Sea Type, East Siberian Type, Canadian, and Polar Ocean Type. The seasonal pattern (winter-summer) of cloud amount and type was described and explained, for the arctic area.

Solar radiation is the main source of energy, and that part of it which is not reflected is of paramount importance in a study of the heat balance of any region. The observational data available for a regional study of solar radiation in the Arctic are still quite inadequate, and the value of stations with short records is limited. Regional differences in insolation are quite marked. The calculation of insolation was based on two steps: determination of cloudless sky radiation, and correction to actual conditions dependent on cloud conditions. The following information is necessary to calculate cloudless sky radiation: Extra-terrestrial radiation, solar height (air mass), ozone absorption, water vapour absorption, atmospheric dust absorption, and ground albedo. Each of these was studied in turn. With these basic data the clear sky radiation at the ground was calculated. Correction to actual radiation on the ground was then performed, using previously published studies on cloud type frequencies and depletion by different cloud types over the Arctic.

Finally, the insolation figures were multiplied by (1 - albedo). For this purpose the previously obtained albedo values were used. Insolation and absorbed solar radiation at the ground were given for grid points for various months.

In climatology and general circulation studies all the energy available at the surface is important, and not only the short wave component. Reliable observations are available only for short wave radiation, and long wave components must be obtained by the application of radiation laws to the known state of the atmosphere.

The long wave radiation emitted from the ground was calculated with the Stefan Boltzmann formula. Long wave radiation received at the ground was determined from the temperature and humidity condition of the atmosphere, first for clear sky conditions (using Elsasser radiation diagram), and then for 10/10 cloudiness with low, medium and high clouds. These values were then corrected to actual cloud amounts and types. An analysis of the individual grid points shows that there are a few quite distinct types of radiation regime: Norwegian Sea Type, Continental Type, Pack ice Type.

Apart from radiation, evaporation and sensible heat flux are the only means of transporting energy from the surface into the atmosphere. They are therefore vital components in all heat exchange considerations. However, they are also the most elusive elements in the energy budget. While radiation calculations can be compared to actual observations, no method exists of measuring and observing evaporation and sensible heat flux directly.

These fluxes were calculated for each month over the Polar Ocean and the Norwegian-Barents Sea.

Evaporation and sensible heat flux were calculated separately for the following areas: Central Polar Ocean, Kara-Laptev Sea, East Siberian Sea, Beaufort Sea, and belts of 5^{o} latitude of the Norwegian-Barents Sea.

A number of other phenomena were investigated in connection with the energy balance study. These are briefly described in the following.

Large quantities of ice are exported from the Polar Ocean, mostly between Greenland and Spitsbergen. An energy budget for the Polar Ocean cannot disregard this energy source, and in the area of melting a corresponding amount must be found on the negative side of the energy balance.

Earlier estimates of ice export were re-examined, and its variations were studied. The wind-caused component of the ice export was found by using Zubov's formula relating ice movement to the pressure gradient. The monthly mean meridional pressure gradients were determined along 80^{o}N and along 65^{o}N, between 20^{o}W and 0^{o}, and between 40^{o} and 30^{o}W, respectively. A 30-year period was used (1921-39, 1946-48, 1949-56), and the wind-caused ice drift was calculated for each month, at 80^{o}N and 65^{o}N.

Information on the East Greenland Current flow is unsatisfactory. Therefore, indirect methods have to be used in order to obtain the ice export by current. Danish charts of ice distribution south of 80^{o}N were used to determine the total amount of ice transported southwards. Subtracting the wind-caused export, the current-transported ice amounts were

obtained. The wind export is relatively high: about ½ of the current export and 1/3 of the total export. Considering variations in the current speed during the year, the resulting total ice export is found to lie about 5% below the estimate of Soviet authors, based on independent calculations for a different observational period.

The atmosphere is nearly transparent for solar radiation but most of the terrestrial radiation is trapped by water vapour, carbon dioxide, and clouds. Some of this absorbed heat is radiated back to the earth's surface. This process is generally called the "greenhouse effect" of the atmosphere.

The effect of water vapour in trapping terrestrial radiation is the dominating influence on the direct loss of heat by radiation from ground to space under cloudless conditions. Water vapour alone can trap 3/4 of the terrestrial radiation. With clouds, in summer over the Central Polar Ocean, only 3% of the terrestrial radiation escapes through the atmosphere.

The Arctic has a strongly negative radiation balance during most of the year. Part of the required energy import is fulfilled by the ocean currents, and the remainder by atmospheric transport (advection). The advection of latent heat was calculated by determining precipitation, evaporation and change in storage of atmospheric water vapour.

The various terms and the calculated values for advected latent heat were tabulated for different areas of the Arctic Ocean. Apart from a

very short spell in fall, the advection of latent heat is always positive in the Polar Ocean, contributing as much as 65% of the annual precipitation. Only 12% of the annual precipitation is contributed by advection in the Norwegian-Barents Sea. The sensible heat transport is far more important than latent heat advection in Arctic areas. The ratio between them is 13:1 in the Central Polar Ocean, and 8:1 in the Norwegian-Barents Sea.

There are two main areas of semi-permanent inversion in the world: the subtropical belt and the polar regions. The polar inversions are generally caused by the energy deficit at the surface. However, the polar inversion is not restricted to the surface layers, but reaches about 2000 m into the atmosphere. The arctic inversion is maintained in its normal position and intensity both by surface cooling and by subsidence, as well as by warm air advection aloft. The inversion over the Polar Ocean is dominant practically during the whole year.

Radiosonde ascent data were used in the investigation, from Stations "North Pole" 4, 6 and 7, and for 30 coastal stations around the Polar Ocean. The data available from the Polar Ocean proper were insufficient to permit a regional investigation. The results referred to the Polar Ocean as a whole, with special weight on the central parts. No month showed less than 59% of the time with an inversion present, and in late winter there is an inversion over the Polar Ocean all the time. The surface inversion has a long mean duration in winter - spring, and a normal duration in summer.

A slightly stable stratification is found over the Polar Ocean in summer. Conditions change drastically towards winter. Very unstable gradients predominate over the warm waters of the Norwegian-Barents Sea, and a sharp gradient exists towards the Polar Ocean, where very strong inversions predominate. The strongest positive vertical temperature gradient (the most intense inversion) is found over the Beaufort Sea and N.W. of the Canadian Archipelago. The most frequent occurrence of inversion is found towards the Siberian side of the Polar Ocean.

The previously published values are used for the present study. It became evident that there are many uncertainties in the determination of the individual terms. It might therefore be argued that it is doubtful if the small changes can be determined, which would result in climatic variations. This would be true especially for the long wave radiation terms, due to their high values. Various methods of determining long wave fluxes will, moreover, give different results. However, this is not particularly serious, if the method used is consistent for all long wave terms. The relative values will remain acceptable, although the absolute values may require adjustments.

SOLAR RADIATION

A. At the surface. The absorbed solar radiation at the surface is the most important radiative term on the income side of the budget. It is governed

by three elements:

(a) water vapour content of the air,

(b) cloud amount and type,

(c) albedo of the surface.

(a) The influence of water vapour on the amount of radiation absorbed at the ground remains largely unchanged with variations in content, and this element can be disregarded. With present-day water vapour content, the cloudless sky solar radiation at the surface is set out in Table 1.

(b) The smallest amounts of solar radiation are received under overcast conditions. There are many possibilities in this case, as clouds can have various optical densities (e.g., depending on cloud top albedo). Table 2 shows the relevant figures for cloud types such as those presently found in the Arctic. A significant change in the general temperature level will give values different from those presented in Table 2. Cloud depletion depends both on location and on season, and the Polar Ocean and its bordering areas seem to be critical, with rapid changes in time and space. The influence of cloud cover can be great, especially with low clouds. Almost one half of the clear sky radiation can be lost. Most of the cloud effect occurs at mid-summer.

A change of 1/10 in stratus cloud cover in June and July would bring a change in total annual depletion of solar radiation as follows:

	65°N	70°	75°	80°	85°	90°N
cal cm^{-2} x 10:	222	208	193	188	193	202

For comparison, evaporation and sensible heat flux are of about this magnitude, and the total annual ocean advection would equal a change in the amount of St of about 3/10 in June and July. It is apparent that very high variations in the total annual solar radiation income must be expected. It would seem that changes in the radiation climate, at least, would be r likely over the Polar Ocean than in lower latitudes. The dampening effect of the ice and water surface will be discussed later.

(c) The surface albedo has the greatest effect on the solar radiation. The lowest value is found for a water surface, whose albedo depends on the solar altitude. Table 3a gives the values used, interpolated from Angström (1925) for water surfaces, and 3b the absorbed clear sky radiation for open water conditions.

The albedo increases sharply for surfaces of ice and snow. A wide range of values have been reported; in the present study a value of 75% has been adopted, from Larsson and Orvig (1962), as an areal average before melting takes place.

Table 3c gives solar radiation absorbed at the surface under different extreme surface and atmospheric conditions. Very great variations are apparent.

B. <u>Solar radiation absorption in the atmosphere</u>. This quantity is higher in polar latitudes than elsewhere, but its value remains small compared to

absorption at the surface. It is rather sensitive to changes in water vapour content, especially with low solar altitude.

One cloud type, St, 500 m thick, was used for the calculation of absorption within clouds. Our knowledge is not sufficient of cloud thicknesses, water content, and heights of the various cloud types to go in more detail. Table 4 gives the absorption values for clear sky and for overcast conditions with St. It is apparent that variations in the atmospheric solar absorption are of rather small importance for climatic change.

LONG WAVE RADIATION

A. The surface balance. The possibility of variations in long wave radiation is much more likely than for solar radiation, and the long wave streams in both directions are closely related. The surface radiation is a function of temperature, and one can assume a wide range of temperatures. The atmosphere's back radiation can, however, not be chosen arbitrarily, as the vertical temperature gradient must be $< 1^{\circ}C/100$ m, which controls the lowest values to be expected for back radiation.

It is difficult to construct theoretical polar atmospheres which include the possible extremes. The following is an example of typical polar conditions, in order to obtain an idea of the importance of radiational exchanges caused by various dynamic conditions.

The most important part of the atmosphere is the lowest 1500 m layer.

Changes in the vertical structure of the atmosphere have a significant influence on the long wave radiation balance, and it would be possible to change the energy budget even without the influence of clouds. By examining the actual cloudfree balance, it becomes apparent that the atmosphere is at present adjusted in the best possible way for the conservation of energy. At 80°N, in March, with a surface temperature around -30°C, the clear sky long wave radiation balance is -92 cal cm^{-2} day^{-1}. In June, with a surface temperature of 0°C, the value is -162 cal. The winter value is the result of an efficient energy conserving stratification, while the summer value is caused by a rather unfavourable condition. A more positive summer condition could only be obtained if the advected energy were much greater than that available at the surface.

According to Vowinckel and Orvig (1965) a monthly winter value of advection for the Central Polar Ocean is 6,000 - 7,000 cal cm^{-2} against a value of 2,000 - 2,500 cal from the surface. Since most of the solar radiation is available at the surface, it is quite clear that abnormally high advection would have to be produced to maintain a strong surface inversion of some 1,000 m thickness in summer. An advection of about 8,000 cal cm^{-2} $month^{-1}$ would be required. This is a higher value than the present winter ones.

It is unlikely that the energy transport through the ice in winter can be much reduced. Vowinckel (1964) showed that the heat flux changes very little once the ice is thicker than 1.5 to 2 m. The main interest in

the present study lies therefore in the calculation of the long wave fluxes for the other extreme: an open Polar Ocean in winter, with a surface temperature of $-1^{\circ}C$ in the coldest month. Using an average gradient of -8 degrees between the surface and 850 mb, and 80% relative humidity, the long wave balance would be -174 cal cm^{-2} day^{-1} for clear sky conditions, i.e., the long wave balance would be almost the same as now in summer.

It can be concluded that, for cloudless conditions:

1. There is little possibility for a change in the long wave balance in summer.
2. In winter, the long wave balance could become much more negative (up to 100 cal cm^{-2} day^{-1}) with an increase of the surface temperature towards that of open water.
3. In winter, the development of a less negative balance than the present seems unlikely.

The most variable factors in the long wave balance are the cloud amount and cloud height. Also, clouds make the vertical structure of the atmosphere very important. The result is a great number of possible variations in the long wave balance.

The cloud amount was changed first in the present investigation, and the atmospheric structure kept unaltered. For purpose of comparison with solar radiation, the clear sky conditions are given as the standard (for long wave radiation this is an arbitrary choice and not an extreme value).

The results of these calculations are given in Table 5. The clear sky values are all negative. The magnitude of the negative balance decreases to the north, firstly because of the lower radiational temperatures and secondly because the stability of the lower atmosphere increases.

The introduction of clouds makes the energy budget less negative, and with St in winter the long wave balance even becomes positive. The change from clear sky conditions becomes less with increasing cloud height. This is a result of lower cloud temperatures and in addition, for Ci, its partial transmissivity of long wave radiation.

The absolute values in Table 5 show a remarkably uniform change from clear sky to overcast throughout the year. Relatively, however, the winter clouds are much more efficient, as the presence of clouds makes the winter inversion most effective. In summer the inversion is much weaker and the clouds accordingly less effective.

As arguments in climatic change discussions, these statements must be used with caution. The presence of a continuous cloud layer, with its positive long wave balance, excludes the prolonged existence of an intense surface inversion. Thus, even if a continuous cloud layer did form over the Polar Ocean in winter, the surface radiation balance would not be increased to the level indicated unless the advection were increased simultaneously to supply the required energy for the increased surface radiation budget.

Table 5 gives, in its last part, figures for an assumed open Polar Ocean. The present temperature lapse rates between the surface and 850 mb at 70°N, 0°E were taken as representative. The results show that the clear sky long wave balance would be much more negative than the present conditions. This is a result of the increased lapse rate. The negative long wave balance, however, would be more than compensated for by the increased solar radiation balance. This is demonstrated by the following figures which show the annual radiation balance of an open Polar Ocean, assuming cloud amounts and types during the year as presently at 70°N, 0°E.

	Solar radiation	Atmospheric radiation down	Surface radiation up	Balance	Change from present
K cal cm^{-2}	57.7	215.4	243.1	+30.0	+27.4

B. Long wave radiation loss to space. The radiation loss to space originates partly at the surface and partly in the atmosphere. Many combinations of conditions are possible, even when a conservative selection is made: temperatures at 300 mb may vary between -60° and -40°, at the surface between -30° and +10°; relative humidity may range from 30% to 90%; the temperature lapse rates may fall between dry adiabatic and strong inversion.

Korb et al (1959) have shown that the main contribution to long wave radiation to space, in spite of the small moisture content, comes from the air high in the atmosphere. The strong inversion of polar regions

would cause conditions somewhat different from those of the temperate latitudes. It is possible to estimate changes in long wave radiation loss to space, resulting from various changes in the atmosphere.

One can imagine two marked changes in climate — firstly a permanently open Polar Ocean and secondly an ocean without any melting. Surface temperatures, assumed for each of these cases, are given in Table 6. The table also shows the calculated clear sky radiation loss to space for two moisture conditions and two sets of values for 300 mb temperature. For comparison, the present actual clear sky radiation loss is also given.

If clouds are introduced, the calculations become rather complicated. The upper surface of the cloud acts as the main radiating body, and there will be many possible combinations, especially as the uppermost cloud surface may be made up of low, medium and high clouds.

To make the problem manageable, it was assumed that the cloud top temperatures do not change much from the present conditions, when considering the frozen alternative over the Polar Ocean. When considering the high temperatures of an open Polar Ocean, the cloud temperatures were interpolated from the height assumptions used in a previous investigation (Vowinckel and Orvig, 1964).

RADIATION BUDGETS

The individual terms can now be combined and various radiation

budgets determined. The results for some extreme examples are presented in Table 7, which shows monthly, seasonal and yearly values for both the surface and for the surface and atmosphere combined. The effects of changes in conditions, especially for the surface, depend on the time of year of occurrence. At present, with relatively high albedo, the summer difference between clear and overcast conditions is small, while the difference in winter is very high. The overcast conditions even show a positive winter balance at the surface. This situation is theoretical and cannot come about in reality.

If the ocean were permanently frozen, the surface balance would be markedly less positive in summer. It is interesting to note that the annual surface balance with an open ocean and clear sky would be nearly similar to that with overcast sky and present surface and atmospheric conditions. This would be a result of the intense heat loss in winter with clear sky and open ocean, which would compensate for the increased summer heat gain. The warmest surface conditions would doubtless be realized with overcast conditions in winter and clear skies in summer. The following annual balances would result:

with present conditions:	+ 23.9
with frozen surface:	+ 3.3 K cal cm^{-2}
with open ocean:	+ 47.1

Only for the frozen surface would the value become less than with completely overcast conditions. This is so, because a certain high value of

albedo would prevent the gain of heat by solar radiation from compensating for the long wave loss. Such conditions are rather unlikely, however. While an open ocean would probably cause little change in cloud amount in summer, the winter conditions would tend to cause more cloud, perhaps between 70% and 80%, values presently found over the Norwegian Sea.

The radiation budgets for a column in the Arctic, including both the earth and the overlying atmosphere, all show a strongly negative balance in Table 7. In reality, an energy balance must exist. Therefore, the radiational deficit gives the necessary heat transport into the Arctic by advection in atmosphere and ocean. The present ocean advection amounts to about 5 K cal year^{-1} (Vowinckel and Orvig, 1962). It is evident that even very large relative changes in this term will remain small compared to the atmospheric advection component.

The last line in Table 7 gives the radiation budget for an open Polar Ocean with cloud conditions as presently found over the Norwegian Sea. This assumption is probably better than that of clear sky or of completely overcast, but it does involve the supposition that circulation over the Polar Ocean should be similar to that now over the Norwegian Sea. This is, in reality, quite unlikely. It is likely, however, that any changes would tend in that direction. Considering the results, and those found for a frozen Polar Ocean, which must require clear winter-cloudy summer (and an

annual surface balance near -14 K cal) it becomes evident that the Polar Ocean is at present in a delicate radiational balance, and relatively minor variations in any term can instigate a gradually intensifying process, ending either in complete freeze-over or in complete melting.

Radiation balance calculations over a year make the tacit assumption that the surpluses in one season can be balanced against deficits in another. Over land surfaces this is certainly impossible. Over ocean surfaces it is more likely, due to the high storage capacity of the water. If it is assumed that the annual temperature variation becomes zero at 200 m (Sverdrup, 1954), and that the temperature variation decreases linearly with depth, an input of 10,000 cal would result in a change of 1 degree C. Considering that part of the solar radiation income in summer is used in radiation to space, an estimate of a temperature variation of 5 degrees for the open ocean would seem to account for the required storage. A second tacit assumption is that no export takes place of radiative energy, i.e., all seasonal surplus goes into storage. This is doubtful. It is only valid if the atmospheric horizontal gradients of temperature and moisture always remain so that wind export is excluded. At present, over the Polar Ocean, this is very nearly the case for monthly means, as shown by Vowinckel and Orvig (1965). As soon as present day conditions are altered over the Polar Ocean, while the surrounding areas are kept as before, it becomes highly doubtful and for an open Polar Ocean it would be unlikely.

The results shown in Table 7 indicate that, under certain conditions

and especially for an open Polar Ocean, the required advection decreases significantly. However, it would be erroneous to conclude from the radiation budget that the still large advective term would be possible, and that an energy balance would therefore be achievable. The energy potentially available by advection in a particular area is only partly dependent on the radiation budget of the area. The advected energy comes from other regions, and the upper limit of available energy is given by the difference in total heat content of the air over the area and of the advected air. If the temperature and moisture content of the air over the Polar Ocean are decreased, then the advective term will increase, provided that the circulation remains constant. If the air over the Polar Ocean becomes warmer and more moist, then the advection will decrease. With an open Polar Ocean in winter it is even possible that this term will become negative. This would increase the heat deficit over the Polar Ocean and might lead to reforming of the ice cover.

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Table 1.
Solar radiation reaching the surface, clear sky, albedo not considered.
cal cm^{-2} $month^{-1}$ x 10

	F	M	A	M	J	J	A	S	O	Year
70°N	132	598	1332	2052	2319	2124	1494	780	267	11098
90°N			1068	2186	2550	2300	1451	222		9777
75-90°N		215	1117	2141	2491	2256	1442	447	36	10145

Table 2.

Solar radiation reaching the surface, various clouds, albedo not considered cal cm^{-2} $month^{-1}$ x 10

	F	M	A	M	J	J	A	S	O	Year
70°N Actual	90	502	1083	1587	1512	1290	834	417	130	7445
10/10 St	59	316	789	1234	1275	1085	716	336	109	5919
10/10 Ac	90	432	1038	1584	1575	1358	942	459	158	7636
10/10 Ci	104	484	1224	1931	2085	1848	1252	621	208	9757
90°N Actual			816	1693	1743	1302	803	102		6459
10/10 St			450	1314	1602	1232	756	57		5411
10/10 Ac			579	1643	1911	1730	942	87		6892
10/10 Ci			871	1990	2316	2096	1206	142		8621
75-90°N Actual		177	864	1590	1690	1341	841	261	16	6780
10/10 St		83	574	1260	1536	1299	771	187	12	5722
10/10 Ac		113	733	1580	1879	1678	976	248	16	7225
10/10 Ci		150	925	1904	2240	2014	1223	351	25	8832

Table 3

Solar radiation absorbed at the surface.

a) Albedo of water surface %

	F	M	A	M	J	J	A	S	O	Year
70°N	47	20	10	7	6	6	9	15	34	
90°N			35	25	12	12	25	60		
75-90°N		44	19	11	8	9	13	31		

Albedo of closed Polar Ocean: 75%

b) S for clear skies, open water (cal cm^{-2} $month^{-1}$ x 10)

	F	M	A	M	J	J	A	S	O	Year
70°N	70	477	1200	1910	2181	1996	1361	663	177	10035
90°N			693	1640	2244	2024	1088	90		7779
75-90°N		130	910	1906	2282	2055	1251	319	18	8871

c) 10/10 St S

	F	M	A	M	J	J	A	S	O	Year
70°N water	31	253	710	1148	1199	1020	652	286	72	5371
75% albedo	15	79	197	309	319	271	179	84	27	1480
actual albedo	22	123	316	580	1020	901	580	185	49	3776
90°N water			293	986	1410	1084	567	23		4363
75% albedo			113	329	401	308	189	14		1354
actual albedo			113	460	705	702	393	23		2396
75-90°N water		46	465	1121	1413	1182	671	129	8	5035
75% albedo		21	144	315	384	325	193	47	3	1432
actual albedo		22	149	441	691	792	455	88	4	2642

Table 4.

Solar radiation absorbed in the atmosphere
cal cm^{-2} $month^{-1}$ x 10

	F	M	A	M	J	J	A	S	O	N	D	Year
clear sky												
70^oN	20	81	165	304	411	427	307	162	19			1896
90^oN			141	298	417	409	313	21				1599
$75-90^oN$		31	144	298	415	413	335	105	9			1750
Overcast (St)												
70^oN	20	87	180	341	474	487	344	174	19			2126
90^oN			144	310	444	437	319	11				1665
$75-90^oN$		32	150	324	466	464	353	108	9			1906

Table 5.

Surface long wave radiation balance

cal cm^{-2} month^{-1} x 10

	J	F	M	A	M	J	J	A	S	O	N	D	Y
70° Actual	-257	-274	-326	-354	-325	-345	-366	-295	-273	-297	-294	-294	
10/10 St	+31	+3	+6	-57	-65	-117	-130	-87	-90	-92	-48	+9	
10/10 Ac	+12	-33	-52	-111	-114	-186	-205	-162	-156	-160	-96	-25	
10/10 Ci	-261	-260	-300	-351	-372	-411	-428	-385	-375	-387	-336	-279	
Clear	-397	-389	-440	-486	-508	-537	-555	-512	-498	-520	-471	-422	-5735
90° Actual	-235	-227	-264	-344	-313	-231	-186	-155	-150	-118	-249	-221	
10/10 St	+152	+117	+130	+36	-40	-78	-59	-34	-51	+33	+105	+151	
10/10 Ac	+134	+100	+115	0	-87	-132	-118	-89	-102	-16	+81	+130	
10/10 Ci	-136	-141	-155	-255	-344	-372	-362	-337	-345	-264	-180	-137	
Clear	-288	-278	-310	-399	-490	-504	-492	-477	-480	-410	-324	-289	-4741
75-90° Actual	-234	-239	-288	-312	-291	-247	-218	-202	-176	-216	-263	-274	
10/10 St	+100	+70	+63	+25	-41	-88	-62	-58	-64	-29	+40	+77	
10/10 Ac	+76	+46	+40	-17	-101	-140	-127	-119	-120	-87	+3	+40	
10/10 Ci	-180	-183	-217	-262	-352	-368	-362	-355	-358	-327	-247	-216	
Clear	-323	-317	-367	-403	-495	-488	-487	-490	-487	-467	-388	-363	-5075
Open Polar Ocean													
Clear	-616	-560	-592	-561	-555	-472	-487	-521	-531	-564	-573	-620	-6652
10/10 St	-213	-195	-183	-132	-117	-117	-100	-99	-132	-155	-180	-223	
10/10 Ac	-275	-252	-245	-222	-186	-160	-134	-133	-198	-220	-243	-282	
10/10 Ci	-470	-428	-443	-417	-353	-331	-342	-358	-384	-415	-435	-477	

Table 6.

$L_{300}^{\uparrow}$, clear sky, actual and assumed conditions

cal cm^{-2} $month^{-1}$ x 10

			J	F	M	A	M	J	J	A	S	O	N	D	Y
Assumed T_{300} °C		a)	-50	-50	-48	-46	-44	-42	-40	-40	-42	-44	-46	-48	
		b)	-60	-60	-58	-56	-54	-52	-50	-50	-52	-54	-56	-58	
T_{sfc}		c)	0	0	-1	0	1	2	3	4	4	3	2	1	
		d)	-30	-30	-25	-20	-15	-10	-5	-5	-10	-15	-20	-25	
$L_{300}^{\uparrow}$ R.H.	90%	a)+c)	1277	1154	1274	1248	1305	1281	1336	1352	1302	1327	1269	1296	15421
		b)+c)	1249	1128	1246	1221	1277	1251	1308	1321	1272	1296	1239	1265	15073
	30%	a)+c)	1358	1226	1352	1326	1389	1362	1426	1438	1389	1414	1350	1376	16406
		b)+c)	1339	1210	1333	1302	1364	1335	1395	1407	1362	1389	1326	1355	16117
	90%	a)+d)	952	860	1011	1035	1135	1158	1259	1259	1158	1135	1035	1011	13008
		b)+d)	927	837	986	1011	1104	1131	1221	1221	1131	1104	1001	986	12660
	30%	a)+d)	980	885	1045	1077	1181	1209	1318	1318	1209	1181	1077	1045	13525
		b)+d)	952	860	1023	1056	1163	1188	1293	1293	1188	1163	1056	1023	13258
Actual clear sky conditions.	75°N		998	902	1020	1065	1243	1284	1370	1349	1245	1194	1059	1032	13761
	80		946	854	980	1032	1200	1266	1352	1324	1212	1144	1020	989	13319
	85		930	832	942	987	1181	1260	1336	1324	1164	1097	969	939	12961
	90		921	823	915	975	1175	1251	1336	1324	1155	1085	960	930	12850
Av. area 75°-90°N			955	860	978	1028	1206	1269	1353	1330	1207	1145	1016	987	13334

$L_{300}^{\uparrow}$ stands for long wave radiation loss to space

Table 7.

Examples of various radiation budget possibilities

75^{o}-90^{o}N, K cal cm^{-2} per time unit

		J	F	M	A	M	J	J	A	S	O	N	D	Wi	Su	Y
Present Surface																
clear	surface	-3.2	-3.2	-3.1	-1.1	+2.5	+6.3	+8.9	+3.6	-2.8	-4.7	-3.9	-3.6	-24.5	+20.2	-4.2
	earth-atm	-9.6	-8.6	-8.9	-5.9	-1.6	+2.7	+4.4	-1.4	-8.9	-11.2	-10.2	-9.9	-67.2	-1.9	-69.2
10/10	surface	+1.0	+0.7	+0.9	+1.7	+2.0	+5.0	+5.9	+3.0	+0.2	-0.3	+0.4	+0.8	+3.7	+17.6	+21.3
St	earth-atm	-10.0	-9.0	-9.5	-7.4	-4.3	-0.8	-0.9	-5.1	-10.0	-11.2	-10.3	-10.2	-70.2	-18.5	-88.7
Frozen Surface																
clear	surface	-3.2	-3.2	-3.1	-1.2	+0.4	+1.4	+0.8	-1.3	-3.8	-4.6	-3.9	-3.6	-25.4	0	-25.4
	earth-atm	-9.3	-8.4	-9.0	-5.9	-2.7	-0.9	-2.4	-5.3	-9.1	-10.9	-10.0	-9.9	-66.5	-17.2	-83.7
10/10	surface	+1.0	+0.7	+0.8	+1.7	+2.7	+3.0	+2.6	+1.4	-0.2	-0.3	+0.4	+0.8	+3.3	+11.4	+14.7
St	earth-atm	-10.0	-9.0	-9.5	-7.5	-5.5	-3.9	-5.6	-7.8	-10.4	-11.2	-10.3	-10.2	-70.6	-30.2	-100.8
Open Ocean																
clear	surface	-6.2	-5.6	-4.6	+3.5	+13.5	+18.1	+15.7	+7.3	-2.1	-5.5	-5.7	-6.2	-35.9	+58.1	+22.2
	earth-atm	-12.5	-11.3	-10.9	-1.7	+9.3	+14.5	+11.6	+2.7	-8.5	-12.7	-12.4	-12.7	-80.8	+36.3	-44.5
10/10	surface	-2.1	-2.0	-1.4	+3.3	+10.0	+13.0	+10.8	+5.7	0	-1.5	-1.8	-2.2	-11.0	+42.9	+31.9
St	earth-atm	-10.7	-10.6	-10.8	-5.3	+2.6	+7.2	+4.3	-2.0	-9.5	-11.9	-11.5	-11.8	-76.8	+6.7	-70.1
Present radiation balance Polar Ocean																
	surface	-2.3	-2.2	-2.2	-0.9	+3.0	+5.3	+6.2	+3.2	-0.4	-2.0	-2.6	-2.6	-14.3	+16.8	+2.5
	earth-atm	-9.5	-8.5	-8.4	-6.2	-2.4	+0.7	+0.2	-3.9	-8.2	-10.3	-9.9	-9.6	-64.3	-11.5	-75.8
Open Polar Ocean N and cloud type as at $70^{o}N/0^{o}E$																
	earth-atm	-10.7	-10.1	-10.2	-3.6	+5.3	+10.0	+7.1	0	-8.4	-11.4	-11.1	-11.3	-73.0	+18.7	-54.3

N stands for cloud amount

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13. ABSTRACT

An a[illegible]s is presented of possible changes in the radiative terms of the Polar Ocea[illegible] energy budget. Theoretical polar atmospheres are discussed with various changes in the radiation balance. It is concluded that the atmosphere is, at present, adjusted in the best possible way for the conservation of energy.

Radiation budgets are presented, for various assumed conditions. The optimum surface conditions would occur with winter overcast and summer clear sky. The earth-atmosphere radiation budget is presented for an open Polar Ocean. Relatively minor variations in any term can result in a complete freeze-over or complete melting. The atmospheric advection required with an open Polar Ocean would decrease significantly from the present. It might even become, in winter, a heat export from the Polar Ocean.

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